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Chemistry Division

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SECTION C-I

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Progress Report: P. A. No. CX5-1

PRODUCTION OF "LIGHT" ISOTOPES IN A HOMOGENEOUS PILE

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ABSTRACT

Calculations have been made on the production of "light" isotopes in a homogeneous pile and their possible poisoning effects. It appears to be improbable that a large poisoning loss will occur as a result of the products of nuclear reactions on the "light" isotopes in the pile. The physical constants of some of the isotopes produced, however, require further investigation in order to be assured of their negligibility. The amounts of several isotopes of general research interest which will be produced in relatively large quantities have been calculated.

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I. INTRODUCTION

A preliminary survey has been made on the production of "light" isotopes as a result of nuclear reactions in the proposed homogeneous unit. This has been done for three reasons: (1) to calculate the poisoning effect of those isotopes whose physical constants are known, (2) to estimate the possible poisoning effect of those isotopes whose physical constants are partially or completely unknown in order to indicate which ones warrant further investigation, and (3) to indicate some of the isotopes of general research interest which may be produced in appreciable amounts.

The term "light" is used to distinguish the isotopes in this study from the so-called "heavy" isotopes, i.e. elements of atomic number greater than 90. The "light" isotopes considered are those formed from the chemicals of the reactor solutions, the structural materials of the reactor tank, and the catalyst added to the solution. The products of nuclear reactions with the fissionable material itself, the fission products and the "heavy" isotopes, have not been included in these calculations.

Since preliminary calculations[1] showed that the yields from alpha and deuteron reactions would be extremely low, detailed calculations were made for neutron reactions only (see Tables 1 - 4). The direct products and the decay products of (n, γ), $(n, 2n)$, (n, p), and (n, α) reactions with all the stable isotopes involved were determined. The poisoning effect or the cross-section to give a poisoning effect[2] of 0.01 was then calculated for the products of these reactions and the daughters of these products.

II. ISOTOPES STUDIED

At the present time two types of reactor solutions, two catalysts, and four tank construction materials are under consideration. In evaluating all of them a total of 29 isotopes must be considered as the starting points for the nuclear reactions.

From the two types of chemical solutions, (1) 0.1 M $NaDCO_3$ and (2) 0.1 M D_2SO_4, the following isotopes are contributed: Na^{23}, C^{12}, C^{13}, O^{16}, O^{17}, O^{18}, H^2, S^{32}, S^{33}, S^{34}, and S^{36}. From the two catalysts, palladium and platinum, the following isotopes are contributed: Pt^{192}, Pt^{194}, Pt^{195}, Pt^{196}, Pt^{198}, Pd^{102}, Pd^{104}, Pd^{105}, Pd^{106}, Pd^{108} and Pd^{110}. The four possible structural materials, beryillium, aluminum, lead, and columbium, contribute the isotopes Be^9, Al^{27}, Cb^{93}, Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208}.

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(1) See Section VI.
(2) For definition see Section IV.

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III. METHODS OF CALCULATION

The number of atoms of an isotope formed by a single reaction in the unit can be given by the following equation:

$$N = \frac{f \sigma M}{\lambda} (1 - e^{-\lambda t}) \qquad (1)$$

where: N refers to the number of product atoms formed.
λ refers to the decay constant of the product isotope.
f refers to the neutron flux of the pile.
M refers to the number of atoms of the isotope exposed to the bombardment.
σ refers to the effective cross-section for the reaction.
t refers to the length of time the isotope is bombarded.

In the case of an isotope of relatively long half-life (i.e. λ is small), equation (1) simplifies to:

$$N = f \sigma M t \qquad (2)$$

In case of a relatively short lived isotope, an equilibrium value is rapidly approached which is given by the expression:

$$N = \frac{f \sigma M}{\lambda} \qquad (3)$$

The production of daughter isotopes by decay of these primary isotopes was calculated by the familiar equations. (cf. Rutherford, Chadwick and Ellis) Equations (2) and (3) were the principal ones used to calculate the amounts of isotopes formed in the unit.

The term "poisoning loss", p, is here arbitrarily defined as the ratio of neutrons absorbed by the poisoning material to those which react with U^{235} to cause fission. This leads to the following formulation of the poisoning loss:

$$p = \frac{\sigma_p \times M_p}{\sigma_f \times M_f} \qquad (4)$$

where: σ_p is the cross-section of the poison.
M_p is the number of atoms of the poison exposed to the bombardment.
σ_f is the cross-section for fission of the fissionable material.
M_f is the number of atoms of the fissionable material.

It is assumed that the poison and the fissionable material will both be exposed to the same neutron flux. Since the denominator of the equation is known[3], the poisoning loss for any isotope can be estimated if the cross-section of the poison and the number of atoms of the poison present are known or can be calculated.

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[3] For U^{235} σ_f = 545 barns and M = 4.4 moles.

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In general, the neutron cross-section of stable isotopes can be estimated, whereas those of radioactive isotopes are unknown.

In the case of the (n, γ) reaction on the stable isotopes, the calculations were straight-forward when the isotopic cross-section was known. When the isotopic cross-section was not known but the total absorption cross-section of the element was known, the cross-section which was used for the individual isotope was the maximum which it could have, i.e. assuming that the cross-section determined for the element was due entirely to this particular isotope(4).

When the cross-section for the primary reaction was known but the cross-section of the radioactive product was unknown, the cross-section for the product isotope which would produce a poisoning loss of 0.01 was calculated. This quantity is shown in the tables. Thus, when the number of atoms and the cross-section of the original stable isotope are known, the poisoning effect for the stable isotope and the cross-section to give a poisoning effect of 0.01 for the radioactive product can be calculated (if the half-life is known or assumed).

In general, if the primary reaction is other than (n, γ), i.e., (n, p), $(n, 2n)$, and (n, α), the cross-section is not known, and hence the poisoning loss can not be calculated. In these cases the poisoning effects of the stable isotopes and the radioactive products were estimated as follows: If σ_1 is the cross-section for the primary reaction and σ_2 is the total neutron absorption cross-section of the product of this reaction, the poisoning loss divided by σ_1, $\frac{"p"}{\sigma_1}$ was calculated if σ_2 was known. If σ_2 was not known, then the $\sigma_1 \sigma_2$ which would give a poisoning loss of 0.01 was calculated. Since the cross-section σ_1 rarely exceeds 1 barn and will, in general, for the neutron energies encountered, be a small fraction of 1 barn, the calculated values of $\frac{p}{\sigma_1}$ will represent the maximum poisoning loss the isotope might produce, and the calculated values of $\sigma_1 \sigma_2$ will represent the minimum value of σ_2 which will give a poisoning loss of 0.01.

In a number of cases, as yet undiscovered isotopes were assumed to have formed. Since their half-lives were unknown, they were assumed to be long-lived, making their poisoning effect a maximum. However, daughters of such isotopes were assumed to form as if the parent isotope was short-lived, again to maximize the poisoning effect.

The poisoning effect of short-lived material was calculated for the equilibrium concentration of that isotope. For the long-lived material the poisoning effect at the time of its maximum concentration, i.e., 30 days for isotopes in the solution and two years for the isotopes in the structural material, was calculated.

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(4) σ_{max} for the individual isotope $= \dfrac{\sigma_a \text{(for element)}}{\text{isotopic abundance}}$

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Values of physical constants were taken principally from the Project Handbook.

It is pertinent to note that in general a neutron loss will not be sustained from reactions such as (α, n), (d, n), (n, 2n) where a neutron is emitted following the capture of the incident particle. Even if the isotope produced by this reaction possesses a high neutron cross-section, there will be no net loss of neutrons. Only if the product of the second reaction in addition has an extremely high cross-section will a neutron loss be experienced. Thus a reaction of the type H^2(d, n)He^3 would not adversely affect the neutron economy, and would probably have a beneficial effect.

For these calculations the values of the cross-sections for thermal neutrons only were used. The effective cross-section in the unit might, therefore, vary appreciably, depending upon the degree of resonance absorption as a result of the difference of the actual neutron energy from the thermal energy. Furthermore, in these calculations the neutron flux was considered to be equivalent for all isotopes. In reality, the neutron flux would drop rapidly in passing outwards from the center of the reactor solution. The calculated results for the isotopes in the structural material will, therefore, tend to be high by a factor of about two or three.

IV. ASSUMED OPERATING CONDITIONS

Operating conditions were assumed to be as follows:

(1) A U^{235} concentration of 1.03 g/l.

(2) A total volume of 1000 l.

(3) A total power level of 10 megawatts, giving an average slow neutron flux of 1.8×10^{14} neutrons/sec/cm^2.

(4) A spherical shaped boiler 51" I.D. using one of the following construction materials: 1" thick beryllium, 0.3 cm of aluminum, 0.3 cm thick lead backed by 0.3 cm of aluminum, or 0.033 cm of columbium backed by 0.3 cm of aluminum.

(5) The chemicals in the boiler solution being either 0.1 M $NaDCO_3$ or 0.1 M D_2SO_4.

(6) Catalyst concentration being 50 mg of either palladium or platinum per liter present as a colloidal suspension in the solution.

(7) Complete purification of the reactor solution at intervals of 30 days.

(8) Tank construction materials changed after a period of 2 years.

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V. NUCLEAR REACTIONS INVOLVING CHARGED PARTICLES

Because of the presence of U^{235} and Pu^{239}, both of which decay by alpha emission, a number of alpha projectile reactions are conceivable. Assuming that the uranium in solution will be 50% U^{238} and 50% U^{235}, and that the Pu^{239} will be allowed to form and accumulate for 30 days, the U^{235} will give rise to 75 alpha disintegration/sec/cc, and the Pu^{239} about 10^5 disintegrations/sec/cc. (U^{234} will give rise to ca. 2000/sec/cc). Since, however, the alpha particles will lose their energy extremely rapidly through ionization processes in the solution, the alpha flux and hence the production of isotopes by alpha reactions will be essentially negligible.

Deuteron reactions are also conceivable as a result of the production of these projectiles by recoil of the deuterium present in the solution from collisions with the fast neutrons(5). In this process the deuterium gains energy from the fast neutrons in average increments of approximately E/2 where E is the energy of the impinging neutron. According to calculations by H. Soodak of the Physics Division, it appears that ca. 10^{12} deuterons/sec/cc of energy above 0.5 mev will be produced in the solution. The life time of a fast deuteron in the solution is approximately 10^{-11} seconds. It thus follows that ca. 10^{10} fast deuterons/sec/cm^2 is the maximum flux that can be expected with a small fraction of the deuterons having energies above 1 mev. Using this value as the deuteron flux and considering one barn as the maximum cross-section obtainable under these conditions for the deuteron reaction, it can be shown that H^2 and O^{16} are the only isotopes present in sufficient quantity to form a product which might cause an appreciabe poisoning. (It was further assumed that no isotope that might form would have a neutron cross-section in excess of 10^6 barns.)

The (d, n), (d, p) and (d, α) reactions are those most likely to take place. The (d, n) reaction which might be expected to occur to an appreciable extent would not adversely effect the neutron economy. The (d, p) reaction would give rise to the same product as an (n, γ) reaction; the latter occuring in relatively much greater yield. The high coulomb barrier for the (d, α) reaction together with the relatively low energies of the deuteron projectiles effectively serves to minimize that reaction. For these reasons and the scarcity of accurate data, no detailed calculations were performed for the isotopes produced by charged particle reactions.

VI. TABULATION OF RESULTS

In tabulating the results, the importance of the various isotopes is compared by calculating one of the following: (1) the poisoning loss (2) the cross-section required to give a poisoning loss of 0.01, (3) the product $\sigma_1 \sigma_2$ required to give a poisoning loss of 0.01, or (4) the quotient p/σ_1. The choice of the expression used for comparison depends

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(5) Fast deuterons, up to energies of 8-10 mev, may be produced by collisions with fission fragments. This source would not be expected to furnish enough deuterons to produce a significant number of reactions.

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on the physical quantities which are unknown. The relative importance of an isotope is ascertained by the size of the poisoning loss or the probability of its having the cross-section (or cross-sections) calculated. For example, a cross-section of 10^2 barns would be extremely unlikely for an (n, α) reaction but relatively probable for an (n, γ) reaction.

Whenever practicable, any uncertainty present in the data, is reflected in the tabulated results in such a manner as to present the maximum effect on the chain reaction.

In Table 1, the number of moles of the isotope present in the unit is tabulated in column 2. The isotopic cross-section is listed in column 3 when known; otherwise the maximum cross-section the isotope can have is listed(6). The poisoning loss of the stable isotope x 100 is listed in column 4. The product of the (n, γ) reaction and its half-life is listed in columns 5 and 6 respectively. In column 7, the neutron cross-section which the isotope in column 5 must have to cause a poisoning loss of 0.01 is shown. The decay products and half-lives of the isotope in column 5 are listed in columns 8 and 9 respectively. The isotopic cross-section is listed in column 10 for the final stable isotope. In column 11, the poisoning loss x 100 of this final product is calculated for those cases where the neutron cross-section can be estimated. In column 12, the cross-section which the isotope must have to give rise to a poisoning loss of 0.01 is calculated for those isotopes for which no cross-section data are available.

In Table 2, columns 2 and 3 list the product of an (n, 2n) reaction on the isotope in column 1 and its half-life. Column 4 lists the product of the two cross-sections which the isotopes of columns 1 and 2 must have to give rise to a poisoning loss of 0.01. The decay products and their half-lives are listed in columns 5 and 6. The isotopic cross-section is listed in column 7. In column 8, the poisoning loss x 100 divided by the cross-section for the (n, 2n) reaction is calculated for those cases where the isotopic cross-section in column 7 can be estimated. In column 9, the product of the cross-sections of the isotopes in columns 1 and 5 necessary to give a poisoning loss of 0.01 is calculated.

In Table 3, columns 2 and 3 list the product of an (n, p) reaction and its half-life. Column 4 lists the products of the cross-sections of the isotopes in columns 1 and 2 necessary to give rise to a poisoning loss of 0.01. It was not necessary to make any further calculations for this table due to the fact that all the isotopes formed through the (n, p) reaction invariably decayed by beta emission back to the original isotope.

In Table 4, columns 2 and 3 list the product of the (n, α) reaction and its half-life. Column 4 lists wherever known the isotopic cross-section of the isotope in column 2. Column 5 lists the poisoning loss x 100 divided by cross-section of the (n, α) reaction, σ_1; and column 6, the products that the isotopic cross-section of the isotopes in columns 1 and 2 must have to give rise to a poisoning loss of 0.01. In

(6) $\sigma_{max} = \dfrac{\sigma_a}{\text{isotopic abundance}}$

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Table 1

Poisoning Effects Caused by (n,γ) Reactions

1 A Z	2 N (moles) of Isotope A Z	3 σ Isotopic(1) (barns)	4 Poisoning Loss x 100 / 100 p	5 A + 1 Z	6 $T_{\frac{1}{2}}$ of A + 1 Z	7 σ Which Will Give p of 0.01 (barns)	8 Decay Products of A + 1 Z	9 $T_{\frac{1}{2}}$ of Decay Products of A + 1 Z	10 σ Isotopic(1) (barns)	11 Poisoning Loss x 100 / 100 p	12 σ Which Will Give p of 0.01 (barns)
$_{11}Na^{23}$	100	0.45	1.88	Na^{24}	14.8 hr	3.8×10^{4}	Mg^{24}	stable	0.45(max)	4.0×10^{-4}	
$_{6}C^{12}$	99	0.0045(max)	1.88×10^{-2}	C^{13}	stable	-	-	-	-	-	
$_{6}C^{13}$	1.1	0.41(max)	1.88×10^{-2}	C^{14}	25,000 yr	1.1×10^{5}	N^{14}	stable	1.7	1.7×10^{-11}	
$_{8}O^{16}$	55,000	0.001(max)	2.08	O^{17}	stable	-	-	-	-	-	
$_{8}O^{17}$	21.4	2.4(max)	2.08	O^{18}	stable	-	-	-	-	-	
$_{8}O^{18}$	112	0.00022	1.03×10^{-3}	O^{19}	29.4 sec	1.3×10^{11}	F^{19}	stable	0.01	4.8×10^{-9}	
$_{1}H^{2}$	110,000	.00065	2.98	H^{3}	23 yr	720	He^{3}	stable	unknown	-	5.8×10^{5}
$_{16}S^{32}$	95	0.47(max)	1.87	S^{33}	stable	-	-	-	-	-	
$_{16}S^{33}$	0.74	61(max)	1.87	S^{34}	stable	-	-	-	-	-	
$_{16}S^{34}$	4.2	0.26	4.6×10^{-2}	S^{35}	87.1 days	1.3×10^{5}	Cl^{35}	stable	44(max)	6.1×10^{-4}	
$_{16}S^{36}$	0.016	2800(max)	1.87	S^{37}	unknown	1.1×10^{3}	Cl^{37}	stable	0.61	5.3×10^{-4}	
$_{4}Be^{9}$	28,800	0.01	12.0	Be^{10}	10^{7} yr	7.5	B^{10}	stable	3525	1.4×10^{-6}	
$_{13}Al^{27}$	1580	0.23	15.2	Al^{28}	2.4 min	1.8×10^{6}	Si^{28}	stable	0.24(max)	4.1×10^{-2}	
$_{41}Cb^{93}$	160	0.01	6.7×10^{-2}	Cb^{94}	66 min	1.4×10^{8}	Mo^{94}	stable	30(max)	2.2×10^{-2}	
$_{82}Pb^{204}$	13	12(max)	6.5	Pb^{205}	data inconclusive	13.7	Ti^{205}	stable	3.1	0.23	
$_{82}Pb^{206}$	205	0.76(max)	6.5	Pb^{207}	stable	-	-	-	-	-	
$_{82}Pb^{207}$	197	0.80(max)	6.5	Pb^{208}	stable	-	-	-	-	-	
$_{82}Pb^{208}$	455	0.00045	8.5×10^{-3}	Pb^{209}	3.32 hr	3.8×10^{4}	Bi^{209}	stable	0.016	1.6×10^{-6}	
$_{46}Pd^{102}$	0.0038	620(max)	9.7×10^{-2}	Pd^{103}	unknown	2.2×10^{4}	Rh^{103}	stable	150	6.8×10^{-3}	
$_{46}Pd^{104}$	0.044	54(max)	9.8×10^{-2}	Pd^{105}	stable	-	-	-	-		
$_{46}Pd^{105}$	0.106	22(max)	9.7×10^{-2}	Pd^{106}	stable	-	-	-	-		
$_{46}Pd^{106}$	0.128	18.3(max)	9×10^{-2}	Pd^{107}	data inconclusive	2.2×10^{2}	Ag^{107}	stable(2)		2.2×10^{-3}	
$_{46}Pd^{108}$	0.126	12.1	6.3×10^{-2}	Pd^{109}	data inconclusive	3.4×10^{4}	Ag^{109}	stable	108	3.2×10^{-3}	
$_{46}Pd^{110}$	0.063	0.63	1.7×10^{-3}	Pd^{111}	26 min	1.5×10^{9}	Ag^{111}	7.5 days	-	-	3.6×10^{6}
							Cd^{111}	stable	23,000(max)	1.8×10^{-2}	
$_{78}Pt^{192}$	0.002	1900(max)	0.16	Pt^{193}	unknown	1.3×10^{4}	Ir^{193}	stable	650(max)	4.9×10^{-2}	
$_{78}Pt^{194}$	0.077	50(max)	0.16	Pt^{195}	stable	-	-	-	-	-	
$_{78}Pt^{195}$	0.090	42(max)	0.16	Pt^{196}	stable(2)	-	-	-	-	-	
$_{78}Pt^{196}$	0.068	4.5	1.3×10^{-2}	Pt^{197}	3.3 day(3)	1.0×10^{6}	Au^{197}	stable	105	6.3×10^{-4}	
$_{78}Pt^{198}$	0.018	4.3	3.3×10^{-3}	Pt^{199}	31 min	6.2×10^{8}	Au^{199}	3.3 day	-	-	4.1×10^{6}
							Hg^{199}	stable	3000	4.5×10^{-3}	

(1) (max) after value indicates σ max was calculated (cf. Section IV).
(2) Stable Ag^{107} possibly possesses a nuclear isomer which decays by isomeric transition with a 40 second half-life.
Stable Pt^{196} possesses a nuclear isomer whichdecays by isomeric transition with an 80 minute half-life.
(3) Pt^{197} consists of two nuclear isomers. To maximize the poisoning effect, the longer lived one, 3.3 day, was used in the calculation.

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Table 2

Poisoning Effects Caused by (n, 2n) Reactions

1	2	3	4	5	6	7	8	9
$^{A}_{Z}$	$^{A-1}_{Z}$	$T_{\frac{1}{2}}$ of $^{A-1}_{Z}$	$\sigma_1 \sigma_2$ to give p of 0.01 (barns)	Decay Products of $^{A-1}_{Z}$	$T_{\frac{1}{2}}$ of Decay Products of $^{A-1}_{Z}$	σ Isotopic(1) (barns)	$\frac{100\ p}{\sigma_1}$	$\sigma_1 \sigma_2$ to give p of 0.01 (barns)
$_{11}Na^{23}$	Na^{22}	3.0 yr	5.1×10^{2}	Ne^{22}	stable	21	3.9×10^{-4}	
$_{6}C^{12}$	C^{11}	20.5 min	7.5×10^{5}	B^{11}	stable	unknown	-	5.1×10^{2}
$_{6}C^{13}$	C^{12}	stable	-	-	-	-	-	
$_{8}O^{16}$	O^{15}	126 sec	1.3×10^{4}	N^{15}	stable	<0.00002	2.1×10^{-4}	
$_{8}O^{17}$	O^{16}	stable	-	-	-	-	-	
$_{8}O^{18}$	O^{17}	stable	-	-	-	-	-	
$_{1}H^{2}$	H^{1}	stable	-	-	-	0.31	6.6×10^{-1}	
$_{16}S^{32}$	S^{31}	3.2 sec	3.0×10^{8}	P^{31}	stable	0.23	4.2×10^{-4}	
$_{16}S^{33}$	S^{32}	stable	-	-	-	-	-	
$_{16}S^{34}$	S^{33}	stable	-	-	-	-	-	
$_{16}S^{36}$	S^{35}	87.1 day	9.1×10^{6}	Cl^{35}	stable	44(max)	8.9×10^{-6}	
$_{4}Be^{9}$	Be^{8}	$\ll 1$ sec		He^{4}	stable	very low		
$_{13}Al^{27}$	Al^{26}	7.0 sec	8.3×10^{6}	Mg^{26}	stable	0.048	3.6×10^{-2}	
$_{41}Cb^{93}$	Cb^{92}	11 day	6.0×10^{2}	Mo^{92}	stable	20(max)	1.5	
$_{82}Pb^{204}$	Pb^{203}	data inconclusive	164	Ti^{203}	stable	0.3	1.8×10^{-3}	
$_{82}Pb^{206}$	Pb^{205}	data inconclusive	10.5	Ti^{205}	stable	3.1	0.30	
$_{82}Pb^{207}$	Pb^{206}	stable	-	-	-	-	-	
$_{82}Pb^{208}$	Pb^{207}	stable	-	-	-	-	-	
$_{46}Pd^{102}$	Pd^{101}	unknown	1.4×10^{7}	Rh^{101}	unknown	-	-	1.4×10^{7}
				Ru^{101}	stable	35(max)	2.6×10^{-6}	
$_{46}Pd^{104}$	Pd^{103}	unknown	1.2×10^{6}	Rh^{103}	stable	150	1.3×10^{-4}	
$_{46}Pd^{105}$	Pd^{104}	stable	-	-	-	-	-	
$_{46}Pd^{106}$	Pd^{105}	stable	-	-	-	-	-	
$_{46}Pd^{108}$	Pd^{107}	data inconclusive	4.1×10^{5}	Ag^{107}	stable(2)	-	1.2×10^{-4}	
$_{46}Pd^{110}$	Pd^{109}	unknown	8.1×10^{5}	Ag^{109}	stable	108	1.3×10^{-4}	
$_{78}Pt^{192}$	Pt^{191}	unknown	2.5×10^{7}	Ir^{191}	stable	1000(max)	4.1×10^{-5}	
$_{78}Pt^{194}$	Pt^{193}	unknown	6.7×10^{5}	Ir^{193}	stable	650(max)	9.8×10^{-4}	
$_{78}Pt^{195}$	Pt^{194}	stable	-	-	-	-	-	
$_{78}Pt^{196}$	Pt^{195}	stable	-	-	-	-	-	
$_{78}Pt^{198}$	Pt^{197}	3.3 day(3)	1.8×10^{7}	Au^{197}	stable	105	3.8×10^{-5}	

(1) See (1) footnote in Table 1.
(2) See second footnote to Table 1.
(3) See third footnote to Table 1.

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Table 3

Poisoning Effects Caused by (n, p) Reactions

1	2	3	4
Z^A	$(Z-1)^A$	$T_{\frac{1}{2}}$	$\sigma_1 \sigma_2$ to give p of 0.01 (barns)
$_{11}Na^{23}$	Ne^{23}	40 sec	2.3×10^7
$_6C^{12}$	B^{12}	0.022 sec	4.2×10^{10}
$_6C^{13}$	B^{13}	unknown	4.6×10^4
$_8O^{16}$	N^{16}	8 sec	2.1×10^5
$_8O^{17}$	N^{17}	unknown	2.4×10^3
$_8O^{18}$	N^{18}	unknown	4.6×10^2
$_1H^2$	-	-	-
$_{16}S^{32}$	P^{32}	14.30 day	1.0×10^3
$_{16}S^{33}$	P^{33}	unknown	7.0×10^4
$_{16}S^{34}$	P^{34}	unknown	1.2×10^4
$_{16}S^{36}$	P^{36}	unknown	3.2×10^6
$_4Be^9$	Li^9	unknown	7.4×10^{-2}
$_{13}Al^{27}$	Mg^{27}	10.2 min	9.5×10^4
$_{41}Cb^{93}$	Zr^{93}	2.5 min	3.8×10^6
$_{82}Pb^{204}$	Tl^{204}	4.23 min	2.8×10^7
$_{82}Pb^{206}$	Tl^{206}	3.5 yr	12.5
$_{82}Pb^{207}$	Tl^{207}	4.76 min	165
$_{82}Pb^{208}$	Tl^{208}	3.1 min	1.1×10^6
$_{46}Pd^{102}$	Rh^{102}	210 day	1.4×10^7
$_{46}Pd^{104}$	Rh^{104}	4.2 min(1)	8.4×10^9
$_{46}Pd^{105}$	Rh^{105}	36 hr	5.3×10^7
$_{46}Pd^{106}$	Rh^{106}	unknown	4.0×10^5
$_{46}Pd^{108}$	Rh^{108}	data inconclusive	4.1×10^5
$_{46}Pd^{110}$	Rh^{110}	data inconclusive	8.1×10^5
$_{78}Pt^{192}$	Ir^{192}	data inconclusive	2.5×10^7
$_{78}Pt^{194}$	Ir^{194}	data inconclusive	6.7×10^5
$_{78}Pt^{195}$	Ir^{195}	unknown	5.7×10^5
$_{78}Pt^{196}$	Ir^{196}	data inconclusive	7.5×10^5
$_{78}Pt^{198}$	Ir^{198}	unknown	2.8×10^6

(1) Rh^{104} consists of two nuclear isomers. The maximize the poisoning effect, the longer lived one, 4.2min, was used in the calculations.

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Table 4

Poisoning Effects Caused by (n,α) Reactions

1 $^{A}_{Z}$	2 $(Z-2)^{A-3}$	3 $T_{\frac{1}{2}}$ of $(Z-2)^{A-3}$	4 σ Isotopic(1) (barns)	5 $\frac{100\,p}{\sigma_1}$	6 $\sigma_1 \sigma_2$ to give p of 0.01 (barns)	7 Decay Products of $(Z-2)^{A-3}$	8 $T_{\frac{1}{2}}$ of Decay Products of $(Z-2)^{A-3}$	9 σ Isotopic(1) (barns)	10 $\frac{100\,p}{\sigma_1}$	11 $\sigma_1 \sigma_2$ to give p of 0.01 (barns)
$_{11}Na^{23}$	F^{20}	12 sec	-	-	7.7×10^{7}	Ne^{20}	stable	2.2(max)	4.3×10^{-3}	-
$_{6}C^{12}$	Be^{9}	stable	0.01	1.9×10^{-5}	-	-	-	-	-	-
$_{6}C^{13}$	Be^{10}	10^{7} yr	-	-	4.6×10^{4}	B^{10}	stable	3525	2.2×10^{-10}	-
$_{8}O^{16}$	C^{13}	stable	0.41(max)	4.4×10^{-1}	-	-	-	-	-	-
$_{8}O^{17}$	C^{14}	25,000 yr	-	-	2.4×10^{3}	N^{14}	stable	1.7	8.1×10^{-10}	-
$_{8}O^{18}$	C^{15}	unknown	-	-	4.6×10^{2}	N^{15}	stable	0.00002	4.4×10^{-8}	-
$_{1}H^{2}$										
$_{16}S^{32}$	Si^{29}	stable	3.5(max)	6.5×10^{-3}	-	-	-	-	-	-
$_{16}S^{33}$	Si^{30}	stable	0.11	1.6×10^{-6}	-	-	-	-	-	-
$_{16}S^{34}$	Si^{31}	170 min	-	-	2.2×10^{6}	P^{31}	stable	0.23	-	1.9×10^{-7}
$_{16}S^{36}$	Si^{33}	unknown	-	-	3.2×10^{6}	P^{33}	unknown	-	-	3.2×10^{6}
						S^{33}	stable	61(max)	1.9×10^{-5}	-
$_{4}Be^{9}$	He^{6}	0.8 sec	-	-	4.0×10^{6}	Li^{6}	stable	825	11,000	-
$_{13}Al^{27}$	Na^{24}	14.8 hr	-	-	1.1×10^{3}	Mg^{24}	stable	0.45(max)	3.4×10^{-1}	-
$_{41}Cb^{93}$	Y^{90}	60 hr	-	-	2.7×10^{3}	Zr^{90}	stable	7.3(max)	5.5×10^{-1}	-
$_{82}Pb^{204}$	Hg^{201}	stable	3820(max)	23	-	-	-	-	-	-
$_{82}Pb^{206}$	Hg^{203}	data inconclusive	-	-	101	Tl^{203}	stable	0.3	2.6×10^{-2}	-
$_{82}Pb^{207}$	Hg^{204}	stable	0.37	3.4×10^{-2}	-	-	-	-	-	-
$_{82}Pb^{208}$	Hg^{205}	5.5 min	-	-	6.2×10^{5}	Tl^{205}	stable	3.1	0.67	-
$_{46}Pd^{102}$	Ru^{99}	stable	47(max)	3.4×10^{-6}	-	-	-	-	-	-
$_{46}Pd^{104}$	Ru^{101}	stable	35(max)	3.0×10^{-5}	-	-	-	-	-	-
$_{46}Pd^{105}$	Ru^{102}	stable	0.25	5.2×10^{-7}	-	-	-	-	-	-
$_{46}Pd^{106}$	Ru^{103}	42 day	-	-	5.1×10^{5}	Rh^{103}	stable	150	8.1×10^{-6}	-
$_{46}Pd^{108}$	Ru^{105}	4.5 hr	-	-	4.5×10^{7}	Rh^{105}	36 hr	-	-	5.6×10^{6}
						Pd^{105}	stable	-	-	-
$_{46}Pd^{110}$	Ru^{107}	data inconclusive		-	8.1×10^{5}	Rh^{107}	unknown	-	-	8.1×10^{5}
						Pd^{107}	data inconclusive	-	-	8.1×10^{5}
						Ag^{107}	stable(2)	-	6.0×10^{-5}	-
$_{78}Pt^{192}$	Os^{189}	stable	62(max)	2.5×10^{-6}	-	-	-	-	-	-
$_{78}Pt^{194}$	Os^{191}	30 hr	-	-	1.1×10^{7}	Ir^{191}	stable	1000(max)	1.6×10^{-3}	-
$_{78}Pt^{195}$	Os^{192}	stable	5.3	9.4×10^{-6}	-	-	-	-	-	-
$_{78}Pt^{196}$	Os^{193}	17 day	-	-	9.2×10^{5}	Ir^{193}	stable	650(max)	-	8.6×10^{-4}
$_{78}Pt^{198}$	Os^{195}	unknown	-	-	2.8×10^{6}	Ir^{195}	unknown	-	-	2.8×10^{6}
						Pt^{195}	stable	-	-	

(1)See footnote(1) in Table 1.
(2)See second footnote to Table 1.

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columns 7 and 8 the decay product and its cross-section is listed. In column 9, the isotopic cross-section of the isotope in column 7 is given whenever known. In column 10, the poisoning loss x 100 divided by the cross-section of the (n, α) reaction, σ_1, is given. In column 11, the product of $\sigma_1 \sigma_2$ necessary to give rise to a poisoning loss of 0.01 is listed.

VII. QUANTITIES OF ISOTOPES FORMED

It is possible to estimate the production of an isotope from its "poisoning loss". The homogeneous unit, when operating at the 10 Kw level, will destroy through the fission process ca. 1.1 moles U^{235} per month. Thus, any isotope causing a poisoning loss of 0.01 will produce 0.011 moles of the new isotope per month. If the poisoning loss of the isotope under consideration is multiplied by 1.1, the number of moles of the product isotope that will form per month in a 10^4 Kw unit will be obtained. These calculations have been carried out for a few of the isotopes and are listed below:

(1) $\underline{H^3}$ - In one month, 0.033 moles (0.1 gm or 500 curies) of H^3 will be produced from the reaction $H^2(n, \gamma)H^3$. Each gram of deuterium will have 0.3 micrograms of H^3 associated with it or 3×10^9 beta disintegrations per minute.

(2) $\underline{S^{35}}$ - The 87 day ${}_{16}S^{35}$, formed by ${}_{16}S^{34}(n, \gamma){}_{16}S^{35}$ reaction, will be produced in considerable quantity provided a reactor solution of D_2SO_4 is used. From Table 1, it is noted that a poisoning loss of 4.6×10^{-4} is experienced in its production. This means that 5.1×10^{-4} moles or 750 curies of S^{35} will be produced per month. Each gram of sulfur in the unit will have 5 micrograms or 0.2 curies of S^{35} associated with it.

(3) $\underline{P^{32}}$ - Similarly, provided a D_2SO_4 reactor solution is used, a considerable quantity of the 14.3 day in P^{32} will be produced in the solution by a $S^{32}(n, p)P^{32}$ reaction. The P^{32} thus produced will be free of carrier. Assuming an effective cross-section for the above reaction of 0.001 barn[7], and correcting for decay, 0.75 milligrams or 200 curies of ${}_{15}P^{32}$ will be produced in one month.

(4) $\underline{C^{14}}$ - The isotope C^{14} can be estimated to form to the extent of 1-2 micrograms/month from the carbonate reactor solution by (n, γ) reaction on C^{13}. It can also be expected to be formed from ${}_8O^{17}$ by an (n, α) reaction. The yield for this latter reaction is probably low, but since O^{17} is approximately 20 times more abundant in the solution, it may represent a significant contribution. The carbon in the solution will be enriched with C^{14} from the (n, γ) reaction by about one part in 10^6. Thus, every gram of carbon from this solution will have associated with it approximately 150,000 beta disintegrations per minute.

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(7) W. E. Cohn estimated a cross-section of $1-2 \times 10^{-3}$ barns for the ${}_{16}S^{32}$ $(n, p)_{15}P^{32}$ reaction in the Clinton pile.

(5) $\underline{Be^{10}}$ - Considerable quantities of the 10^7 year Be^{10} will form in the reactor tank if it is contructed of beryllium. In 2 years ca. 39 grams or 0.13 curies of ${}_4Be^{10}$ will form. Each gram of the stable Be will have 0.13 micrograms or 10^6 disintegrations per minute of Be^{10} associated with it.

(6) $\underline{Na^{22}}$ - Similarly the 3 year ${}_{11}Na^{22}$ may form in the $NaDCO_3$ reactor solution by the (n, 2n) reaction on ${}_{11}Na^{23}$. Assuming an effective cross-section of 10^{-4} barns for the above reaction, 4.8×10^{-6} moles or 0.55 curies of Na^{22} will form in one month. Each gram of stable Na^{23} will have 0.05 micrograms or 5.4×10^7 disintegrations per minuted of Na^{22} associated with it. Although about 1.3×10^5 curies of Na^{24} will be present in solution at the end of one month toghether with the Na^{22} and the stable Na^{23}, a separation can be achieved by permitting the solution to cool. Due to short half-life of Na^{24} (14.8 hours), the Na^{24} activity would drop to less than 1% that of the Na^{22} activity in a period of approximately 15 days.

VIII. CONCLUSIONS

On examining the results in Section VII, it is seen that no large poisoning effect can be expected with certainty from the product of nuclear reactions on the "light" isotopes in the homogeneous pile, i.e., the calculations reveal low poisoning losses in all cases where the physical constants are known completely.

It, furthermore, appears unlikely that a large poisoning loss will be experienced in these cases in which the physical constants are not all known. Some of these isotopes might become important, however, if an unusually high neutron cross-section were to appear as in the case of Xe^{135}. Several isotopes are here listed which may merit further investigation.

Depending upon the yield of the (n,α) reaction on a Be^9 to give He^6 which decays with a half-life of 0.8 sec. to Li^6, an appreciable poisoning loss may be experienced due to Li^6 (σ_c = 825b). Even if the effective cross-section for the (n,α) reaction is as low as 10^{-4} barns, a poisoning loss of 0.01 will be experienced in 2 years.

Similarly, if Li^9 has a half-life of the order of days, if the effective cross-section for the Be^9 (n, p) Li^9 reaction is 10^{-3} barns, and if Li^9 has a capture cross-section of 10 barns, a poisoning loss of 0.01 will be experienced in 2 years.

Tl^{205}, Tl^{206}, Hg^{201}, Pb^{205}, and perhaps other isotopes formed from Pb are also among these isotopes which would need relatively low cross-sections to cause an appreciable neutron loss.

In general, the isotopes formed from platinum and palladium are present in insufficient quantities to contribute much to the poisoning effect, although they have rather large neutron cross-sections.

Furthermore, the unit will produce a number of "light" isotopes of general research interest, some of them pure and some of them with a sufficiently high specific activity to be useful for most tracer work. It may also produce, depending on the physical constants, some "light" isotopes hitherto unknown.

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